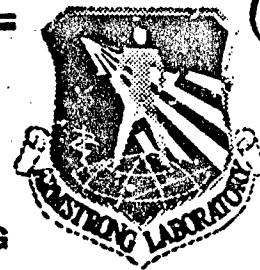
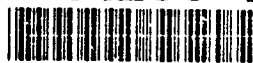


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**LEAK DETECTION BY ACOUSTIC EMISSION MONITORING
PHASE I: FEASIBILITY STUDY**

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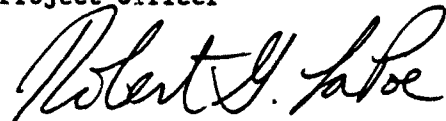
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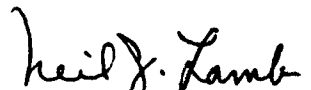
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PREFACE

This technical report was originally prepared by MSB Systems, Inc., 50 Washington Street, Norwalk, CT 06854 under Contract Number F08635-87-C-0366 for the Air Force Engineering and Services Center. The work was accomplished as a SBIR Phase 1 effort, but the technical report was never published.

This report summarizes work accomplished between August 1987 and March 1988. Mr Hari B. Bindal was then the project manager.

Although the research is over 4 years old and the distribution limitation for SBIR has expired, the report is being published by this Directorate because of its interest to the DOD scientific and engineering community.

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SUMMARY

An SBIR Phase 1 study has been performed to assess the feasibility of detecting underground storage leaks by acoustic emission monitoring (AEM) techniques. Leak detection is required to control potential environmental hazards and reduce economic loss. An extensive technical literature review established that distinguishable AE signals will be generated when the storage tank is subjected to deformation stresses. A parametric analysis was performed which indicated that leak rates less than 0.1 gallons per hour can be detected for leak sizes less than 1/32 inch with 99% probability, if the transient signals were sensed with an array of accelerometers (cemented to the tank or via acoustic waveguides), each having a sensitivity greater than 250 mv/g over a frequency range of 0.1 to 4000 Hz, and processed in a multi-channel Fourier spectrum analyzer with automatic threshold detection. An acoustic transient or energy release processor could conceivably detect the onset of the leak at the moment of fracture of the tank wall. The primary limitations to realizing reliable and robust AE monitoring of underground fluid leaks are the various masking noise sources prevalent at Air Force bases, which are attributed to aircraft, motor traffic, pump station operation, and ground tremors. It is recommended that a Phase 2 effort primarily address the measurement, characterization, and suppression of these noise sources.

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SECTION I

INTRODUCTION

A. OBJECTIVE

NSB Systems, Inc. has performed an SBIR Phase 1 study, to assess the feasibility of detecting underground storage leaks by acoustic emission monitoring (AEM), for the AFESC, Tyndall AFB, under Contract No. F08635-87-C-0366. Emphasis was placed on understanding the relevant physics controlling the AE process and obtaining a quantifiable measure of the AE levels. Broadband processors successfully employed in sonar and radar applications, such as the Product Array Processor (PAP) and Fourier Spectrum Processor (FSP), were evaluated for processing continuous leak "acoustic signatures". A primary objective of the study was to use the results of the research to define the required AEM system specifications and to formulate the AEM system development, testing, and evaluation program in Phase 2.

The primary goals of the Phase 1 study are to:

1. Establish the proof-of-concept of reliable and robust leak detection and localization by acoustic emission monitoring (AEM), over a broad range of soil conditions.
2. Evaluate AEM system design feasibility utilizing a Product Array Processor or a Fourier Spectrum Processor, including engineering and operational constraints.
3. Estimate the attainable pinpointing accuracy and multi-leak resolution for a distributed system of underground storage tanks.
4. Define the AEM system specifications for fixed and portable operation.
5. Design the experimental laboratory and field tests required for AEM system development and evaluation in Phase 2.

B. BACKGROUND

Leak detection is required to control potential environmental hazards and reduce economic loss. In a military scenario, it is also required to guarantee sufficient resources upon demand. Locating leaks in underground piping is a major maintenance cost in distribution operations. The significance of the problem is supported by recent estimates by the Department of Transportation (Research and Special Programs Administration, Washington, D.C.) that for gas leaks alone, the average detected leak rate in the United States and Canada is about one per mile of pipeline per year. Each year, about 650,000 main and service leaks are reported to the Federal Government and repaired, at an approximate cost of \$ 850 million. Considerably more are detected but not repaired. It is reasonable to assume that petroleum fuel leaks and those from other high value liquids, in underground storage tanks and pipelines, would have a similar leak frequency.

Over the past thirty years, measurements have established that

when a solid material is deformed, stress energy may be released in a number of forms, including thermal and acoustic emissions. The acoustic energy is emitted as a series of short duration, broadband pulses, and have been detected over a range of frequencies from audio to HF. The rate of emitted pulses is closely correlated to the degree of plastic flow up to crack formation. The acoustic emission signature lends itself to broadband energy detection, spectrum analysis, and pattern recognition techniques developed in other fields.

C. SCOPE/APPROACH

The results of the research are given in Section II. Highlights of an extensive technical literature review are given in Section II.A. In Section II.B, a parametric analysis is performed where the remote AE detection of underground leaks is formulated as a passive sonar detection problem. All detection, medium and target parameters are defined and the minimum detectable leak particle acceleration levels (\ddot{u}) are computed as a function of leak depth for various soil compositions. Utilizing the model formulated by Morse and Ingard for the generation of acoustic power due to turbulent flow, a relationship is derived between (\ddot{u}) and the volumetric discharge rate (Q) from a leak orifice of area (A). The required accelerometer element characteristics and its coupling to the storage tank are given in Section II.C. The effectiveness of product array and Fourier spectrum processors for processing AE leak signatures is discussed in Section II.D. Based upon these results and on AFESC requirements, the desired AEM system specifications for both automatic and portable operation are given in Section II.E. The man-made and naturally-occurring disturbances which tend to mask the AE leak signatures in an operational environment are delineated in Section II.F. Section III reviews the Phase 2 AEM system test plan, which includes laboratory and field tests and post-data algorithmic processing. Emphasis is placed on obtaining a comprehensive set of recordings of noise sources, including air-borne, ground motor traffic, and plant station, at the field test site(s). Finally, the conclusions of the Phase I study and recommendations for both immediate and long-term research are given in Section IV.

SECTION II

RESEARCH RESULTS

A. TECHNICAL LITERATURE REVIEW

Over the past fifteen years, a considerable number of fine acoustic emission (AE) studies were conducted by the team of Koerner, Lord, and their associates (K-L) at Drexel University (Philadelphia, PA). These studies covered a broad range: from making field tests and developing an acoustic emission monitoring system for determining earth and waste dam stability (References 1 - 5), to the acoustic emission detection and monitoring of leaks from underground gasoline storage tanks (Reference 6) and buried pipelines (References 7 and 8).

It is now well established that AE monitoring can be effectively employed to assess soil stability of dams, dikes, retaining walls, and lagoon embankments. In soils, the application of stress produces potential energy which is partly converted into acoustic energy when the cohesion between, and the friction of, the soil particles are overcome. In rocks, this phenomenon is sometimes referred to as "microseismic activity", "rock noise", or "seismo-acoustical activity". Microseismic transients have a measured duration of 0.25 to 10 milliseconds, resulting in a broad spectrum from 100 to 4,000 Hz (Reference 9). K-L found that most of the acoustic emissions in soils are in the frequency range of 500 to 8,000 Hz, in the audible range. The acoustic emission levels and mechanisms involved vary with soil type. Field tests on earth dams indicated a close correlation between AE and seepage flow rate along the dam. Other studies (Reference 10) have shown that turbulent water flow through soils, at rates of 0.3 to 1 cm/sec, will generate acoustic signals with frequencies up to 500 Hz. The AE levels were also found to increase with increasing soil density and increasing variation in soil grain size.

Due to the high attenuation of acoustic emissions through soils at frequencies above 1,000 Hz, acoustic waveguides (attached to an accelerometer, amplifier, and electronic counter) are generally employed to transmit these emissions to the surface for monitoring. K-L used steel rods 0.5 inch in diameter, driven vertically down from the top of the embankment slope to within one meter of the foundation. The accelerometer response was from 100 to 5,000 Hz.

Acoustic emissions are also the internally-generated sounds produced in materials, such as metal and plastic, when they are subjected to stress such that they undergo deformation, fracture, or both. AE occurs after "yield", the end of the material's elastic state and the beginning of its plastic state. A strong correlation exists between stress vs. strain and stress vs. AE. The stress vs. AE curves are shown in Figure 1 for 1" and 2½" diameter steel pipes tested in compression, tension, bending and torsion. The

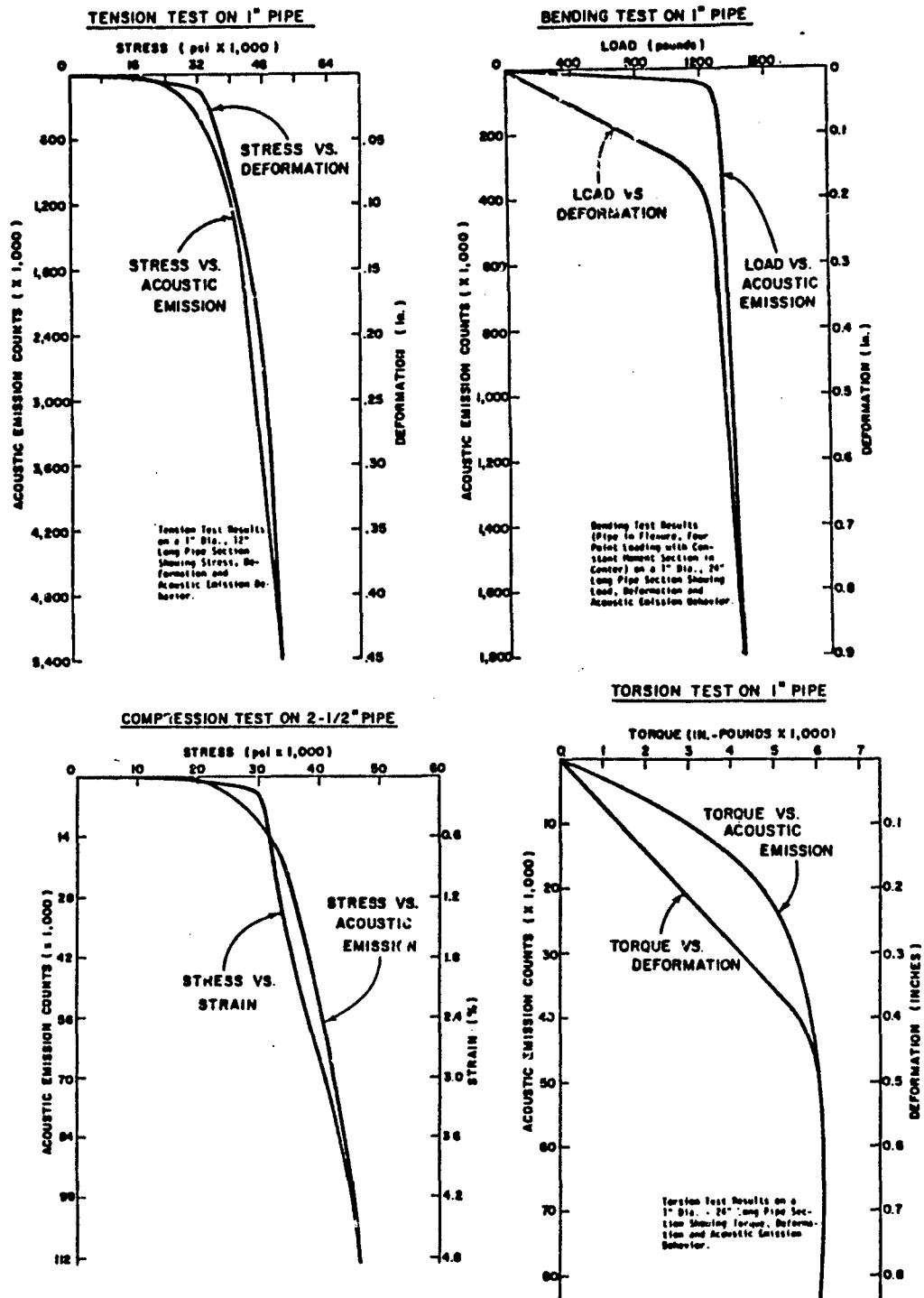


Figure 1. Acoustic Emission Monitoring for Steel Pipes Tested in Compression, Tension, Bending and Torsion (Reference 7)

piezoelectric transducers used for AE monitoring were resonant at 175 kHz, with a filter bandwidth from 125 kHz to 250 kHz. It is seen that the AE rate is almost linear in the plastic range. Acoustic emissions were also measured when the pipeline generated a leak as little as 0.013 inches in diameter. The AE rates were found to increase linearly with internal pipe pressures for air, water, or oil leaks, with the hole diameter as the varying parameter. In these tests, the liquids were under pressure of up to 200 psi, and the pickup accelerometer had a flat frequency response from a few Hz to 10,000 Hz. At a given internal pressure, the larger the hole size the greater the AE rate. Figures 2(a) and 2(b) show these results for water and oil as the escaping fluid. The leak hydrodynamic noise is a friction phenomenon: air is more emissive than water, which is more emissive than oil; the more viscous materials produce lower AE levels. Thus, the cumulative AE count is lower for oil than water for a given pipe diameter and leak orifice. AE monitoring may prove to be effective for assessing pipeline stability and safety. High AE levels would imply a serious stress or leak situation; low AE levels would imply an equilibrium or safe condition.

Many of the 4,000,000 underground gasoline tanks in service in America are losing various amounts of their fuel through leaks. To address this condition, laboratory tests were made by K-L to evaluate the AE activity produced by water escaping from a 30 gallon steel tank for leak diameters from 0.035" to 0.109", as the water pressure was varied from 0 to 15 psi. The AE response curves are shown in Figure 3, for an accelerometer resonant at 5 kHz mounted on the tank. Pressure levels greater than 10 to 15 psi appear to be required to generate a quantifiable AE signal (greater than 400 counts per second). Results also indicated that this leak detection method, as configured, was prone to environmental noise masking.

Leak source location via AE monitoring is also possible. Analysis has shown that a longitudinal wave is preferred for monitoring, due to its lower attenuation, over other types of propagation modes. The attenuation of longitudinal waves is approximately 0.10 dB/ft for frequencies of 5 to 40 kHz, independent of the pipe coupling mechanism, pipeline coating, or pipeline cover. Transverse waves have larger attenuation coefficients at these frequencies. The literature shows that from 1 Hz to 10 MHz, $\alpha = 10^{-6} f$, where (α) is the attenuation coefficient in dB/ft and (f) is the frequency in Hz. The results of a field study, plotted in Figure 4, showed that a pulsating leak from a 3" diameter pipe, at about 10 psi, produced measurable AE signals for approximately 100 feet from the leak. The North-South track data was replotted (see Figure 5) to derive the source location within an error of a few feet. The test data clearly showed that the leak energy spectrum must be high enough to avoid ambient noise masking (airborne and ground transmitted vibrations), and low enough to avoid excessive signal attenuation. The source location of AE signals has also been used in the in-plant monitoring of nuclear reactor pressure vessels (References 11 and 12). The location of a

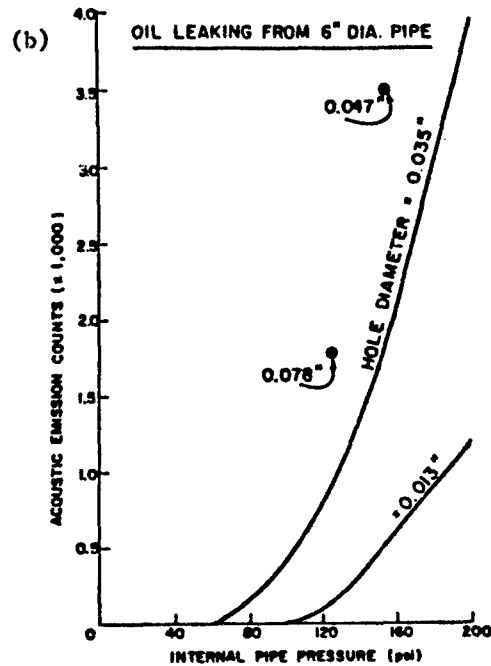
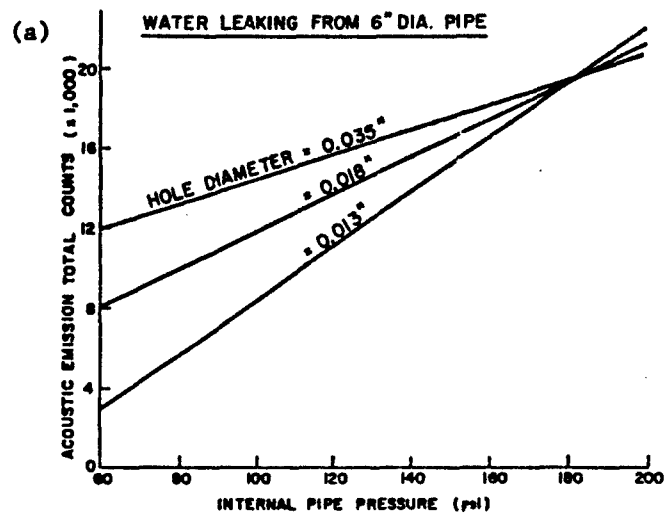


Figure 2. Acoustic Emission Monitoring for Water and Oil Leaking from a 6" Diameter Steel Pipe (Reference 7)

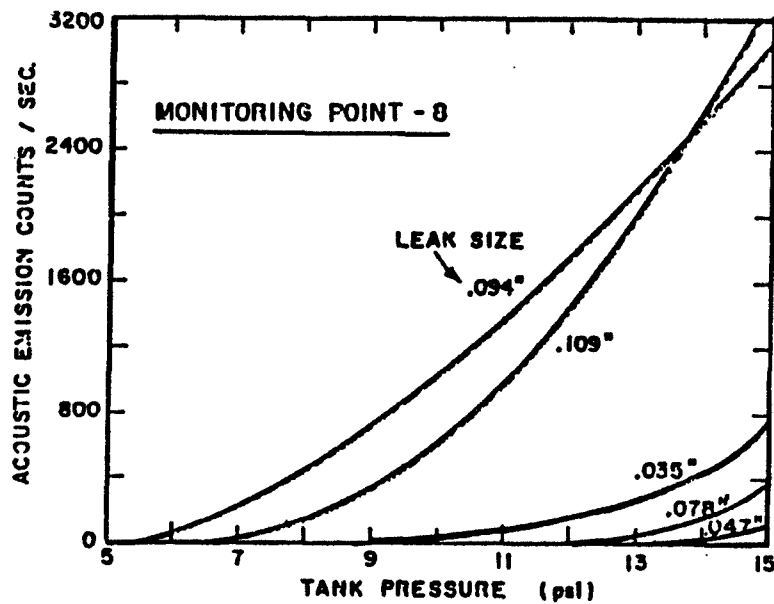
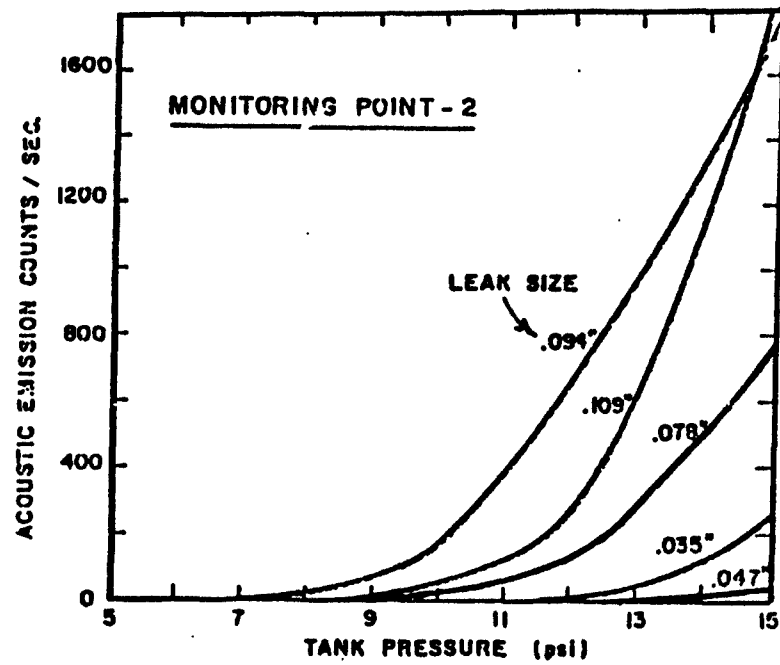


Figure 3. Acoustic Emission Response Curves as a Function of Tank Pressure for Various Sizes of Escaping Water for Two Monitoring Locations Around the Gasoline Tank (Reference 6)

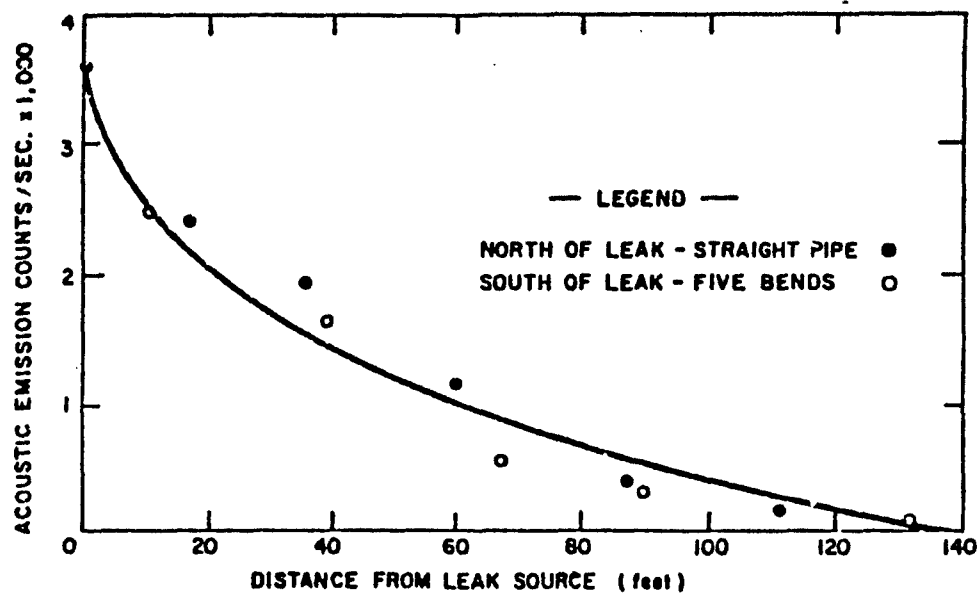


Figure 4. Field Results of Acoustic Emission Count Rate for a Pulsating Leak in a 3" Diameter Pipeline as a Function of Distance from the Leak and on Both Sides of the Leak (Reference 8)

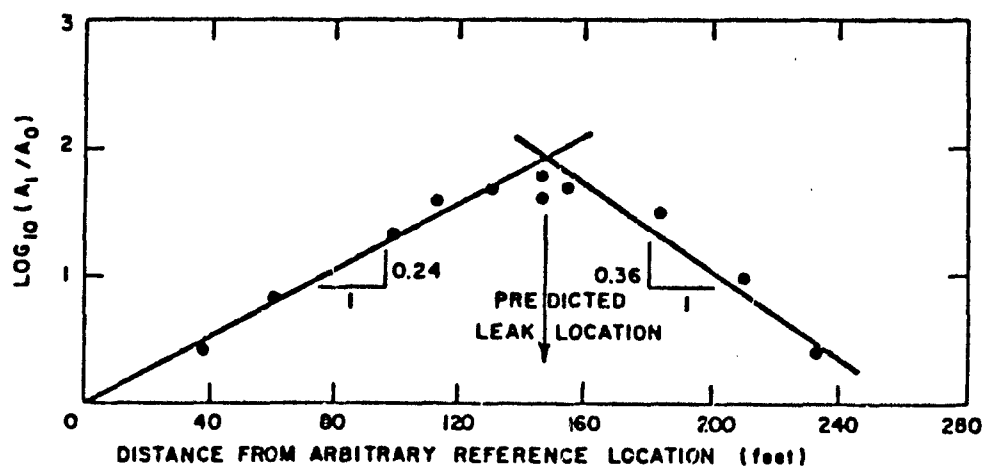


Figure 5. Data of Figure 4 Replotted to Illustrate the Method of Leak Source Location Using the AEM Technique (the actual leak was 145 feet from the reference datum) (Reference 8)

leak was estimated by employing a seismic-like computational method which combined the data of various transducer spacings (relative to a grid system), the acoustic velocity in the pressure vessel wall, and the relative times-of-arrival of signals to the sensor.

Robinson (Reference 13), with the Exxon Nuclear Co., developed a sophisticated AE test system for integrity analysis of complex piping systems and long runs of buried piping. Passive acoustic sensors were located on the structure to detect minute signals generated by flaws or discontinuities in the structure when stressed. A Time Analysis Computer (TAC) was used to determine the difference in times-of-arrival at various transducer locations. An Energy Release Processor (ERP) was used for both leak detection and location. The ERP system can display the rate of acoustic energy per unit stress (being released from the structure) vs. the internal vessel pressure, which can provide an early warning of significant defect growth. A typical acoustic energy release pattern is shown in Figure 6. The number of required transducer spacings on the structure under test are a function of the pipe material, the condition of the pipe, and the type of welds used. A remote acoustic probe was developed, consisting of an acoustically insulated transducer and a pointed steel contact shoe, attached to a hollow shaft. The shaft contained a preamplifier and a battery power supply.

Acoustic emission monitoring has also revealed the presence of significant cracks in welds of stainless steel steam lines in a thermal power plant (Reference 14). The main problems of this application were the high temperature of the steam line (538° C) and the intense background noise. The high temperature problem was solved by using acoustic waveguides welded on the steam-line wall. Noise rejection was obtained by using specially designed sensors and by high-pass filtering the AE signals before preamplification.

Although the AEM literature was primarily concerned with metal pipelines and storage tanks, AE patterns have also been successfully measured for fiber-reinforced composites (Reference 15), and composite rocket motor cases (Reference 16).

Huebler, of the Institute of Gas Technology (Chicago, Ill.), has conducted a number of laboratory and field tests to determine the effectiveness of acoustic detection and pinpointing of leaks in low pressure gas distribution systems (Reference 17). By inserting a sensitive microphone into the pipeline, a 5/16 inch leak was detected at pressures as low as 1/4 psig, and pinpointed to less than ±6 inches. The spectrum of a typical leak signal is shown in Figure 7, which depicts the acoustic energy to be primarily distributed over the range of 1-50 kHz. Most of the noise generated by the flow of gas through the pipeline was measured to be below 500 Hz. Other tests were conducted (Reference 18) to detect leaks in gas mains with operating pressures greater than 15 psig. Probes were driven into the ground, with high-sensitivity accelerometers attached, to sample both

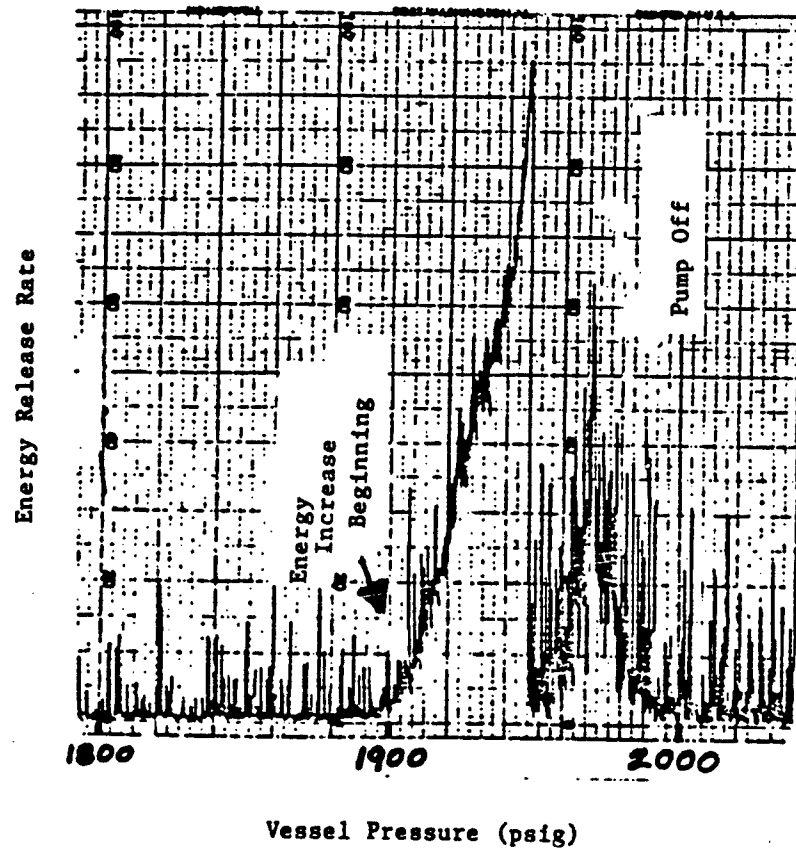


Figure 6. Acoustic Energy Release Pattern Reveals Growth of Significant Defect in Pipeline (Reference 13)

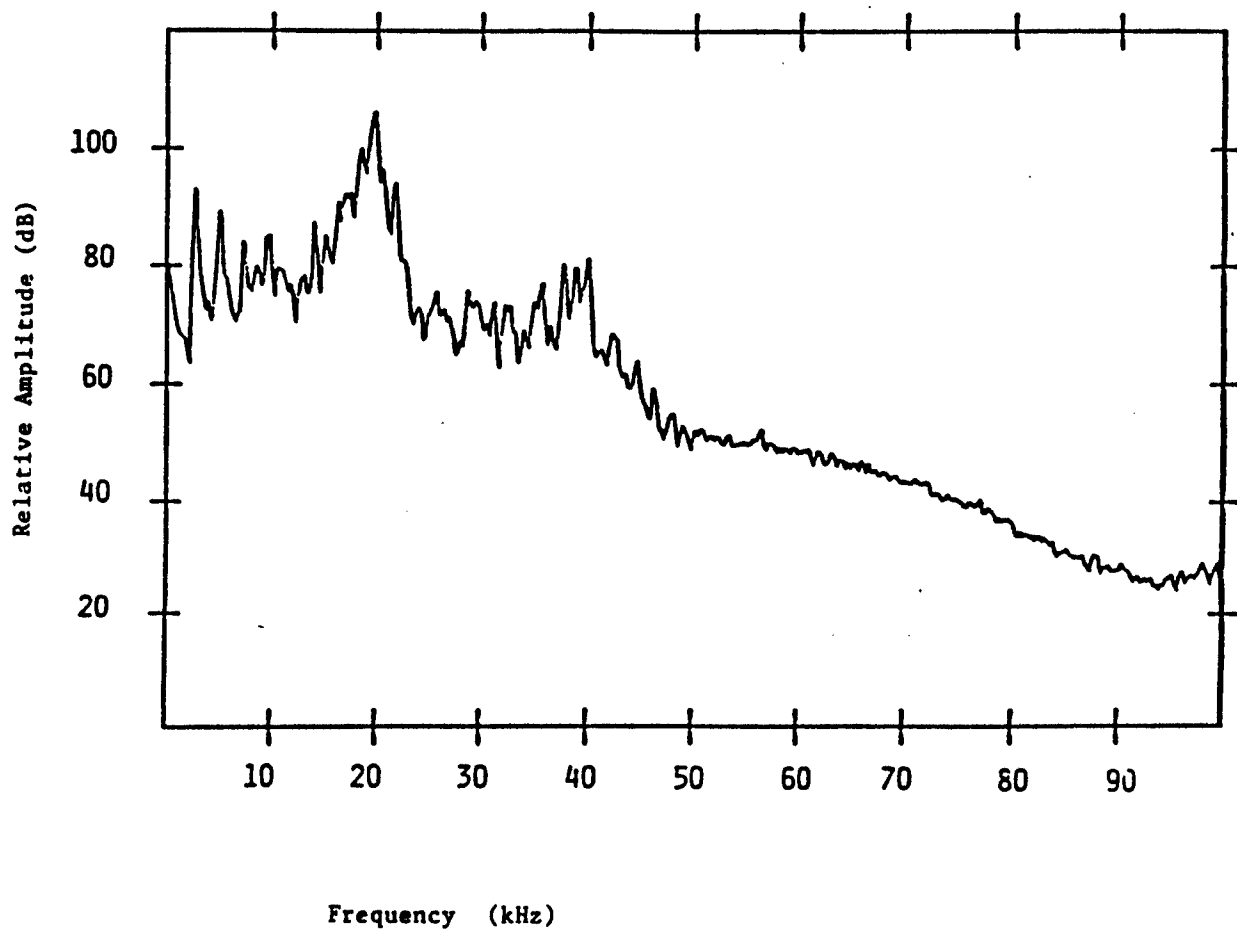


Figure 7. A Typical Acoustic Leak Spectrum

the leak signal plus noise field and the background noise field only. This approach was plagued with high false alarms due to background interferences. To eliminate most of the low-frequency noise, and considering the ground attenuation of the leak signal, the effective frequency range of accelerometer operation was limited from 1,000 to 10,000 Hz.

A considerable amount of time was also spent in the study to improve understanding of the physics controlling the AE process. The objective was to try and obtain a prediction model for the leak particle acceleration level. This is necessary, to devise a robust AEM system and to give insight into the design of a meaningful experimental test program in Phase 2. In addition, the model will facilitate any required modification of the AE tests, and the proper extrapolation of the test data.

The theory of sound generation in a turbulent fluid which is unconstrained by solid boundaries was originally developed by Lighthill (References 19 and 20). Representing the fluctuations of turbulence by an acoustic oscillating quadrupole, he deduced that "The mean square density fluctuation radiated from turbulent flow increases with the eighth power of the flow velocity." Tests have varified Lighthill's theory. Ffowcs Williams (Reference 21) used Lighthill's acoustic analogy to formulate the hydrodynamic noise produced by turbulent flow. Morse and Ingard (Reference 22) presented a very lucid and insightful description, and quantification, of the portion of the turbulent fluid flow which is converted into acoustic energy. Their model was the basis for our analysis of the minimum detectable leak particle acceleration level of the escaping fluid, given in Appendix B.

B. PARAMETRIC ANALYSIS

1. AEM System Model

In the literature survey, it was clearly established that acoustic emissions occur in materials, such as metal or plastic, when they are stressed beyond their elastic limit. The reliable and efficient detection of these emissions depends on the environmental masking levels for the given application. For a complete overview, this study also included an analysis of the detection of the escaping fluid, after rupture (of the storage tank or pipeline) occurs.

The AEM model used in the parametric analysis is shown in Figure 8. It represents a top-down approach in determining the feasibility of remote AE detection of underground leaks. Quantitatively, the analysis was formulated as a passive sonar detection problem, where the objective is to detect a radiating acoustic leak signature with high probability (PD) and low false alarm rate (FAR). The system model considered the soil composition and structure, the leak depth and rate, the acoustic array geometry on the

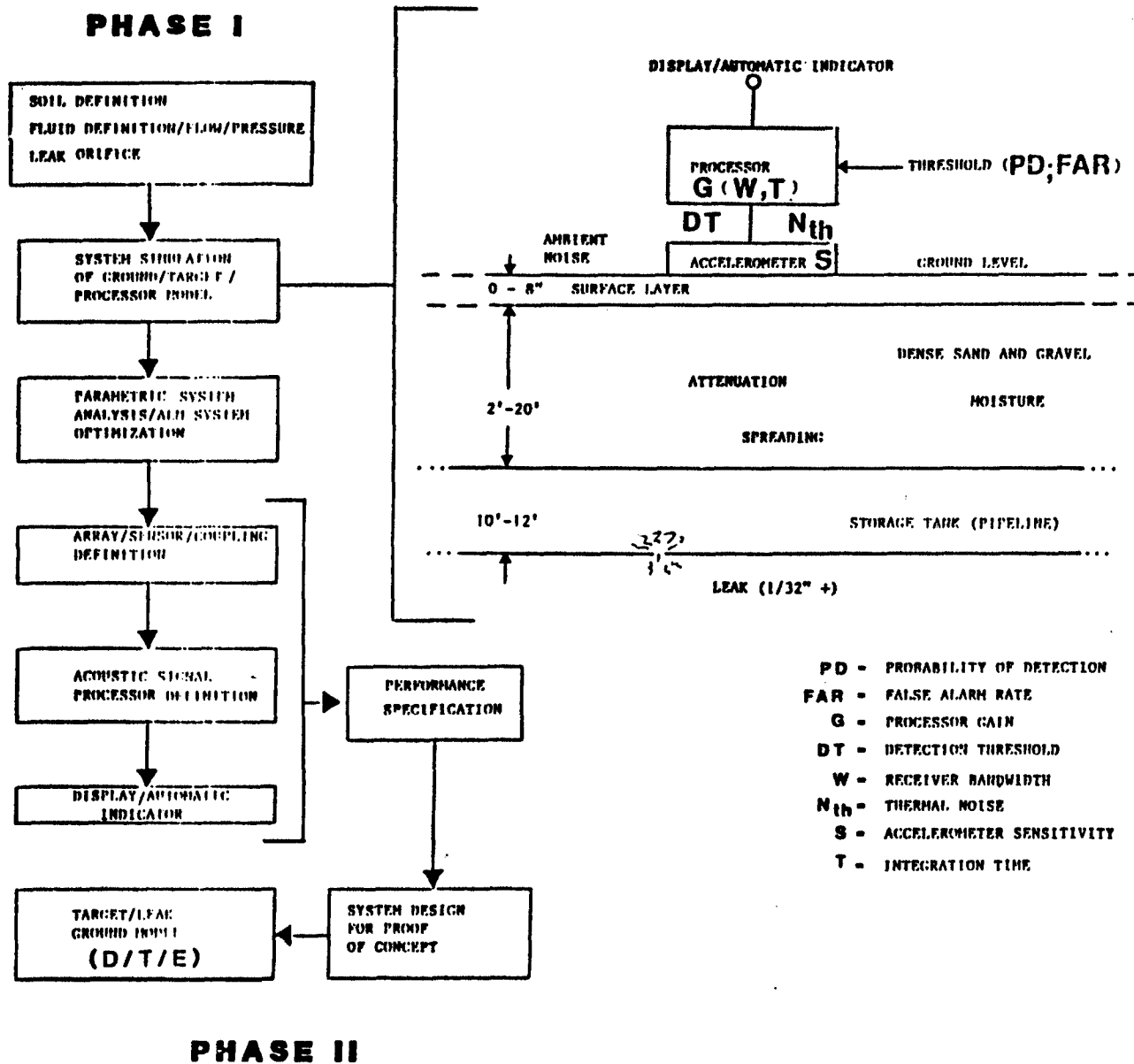


Figure 8. The AEM Model for Parametric Analysis

ground surface, and the type of signal processor employed. The system parameters considered were: The transmission losses through the composite ground material, the voltage sensitivity of the accelerometer, the thermal noise for a given receiver bandwidth and sensor output impedance, and the detection threshold for a specified probability of detection (PD) and false alarm rate (FAR).

The technical approach was to first establish the required post-processor threshold for a desired PD and FAR, utilizing the Receiver Operating Characteristic for an ideal incoherent processor. An incoherent processor is sensitive only to the amplitude modulation of the received waveform, and was required for this application because the phase structure of the acoustic emissions is unknown. For cost-effective AEM operation, it was required that the PD be at least 90% and that the FAR be less than once per twenty-four hours for a portable system, and once per year for an automatic detection system. The computed threshold and processing gain, the latter being a function of the receiver bandwidth (W) and integration time (T), established the detection threshold (DT) of the system. This, by definition, is the minimum signal-to-noise ratio (SNR) "detectable" at the output of the accelerometer. This SNR estimate should be corrected for real processor losses, depending upon the specific processor architecture selected. A computation of the thermal noise, together with the value of DT, produced an estimate of the minimum detectable signal level (MDSL). The MDSL can be referred to the accelerometer/ground surface interface by using the voltage sensitivity of commercially available accelerometers. The resulting particle acceleration level, in turn, can be referred back to the leak orifice by considering the attenuation and dispersion of sound in various sediments. The acceleration level at the leak orifice can be related to the velocity of the fluid passing through the orifice, or to the volumetric leak rate for a given leak size. The study considered leak sizes from 1/32 inch to 1/8 inch, JP-4 jet engine fuel, and a steel or fiberglass storage tank, 90 feet long with a 10 to 12 foot diameter, buried 15 to 20 feet deep in the ground (consisting of sand and gravel with some moisture). These parameters were specified by AFESC. The detailed derivation of the minimum detectable particle acceleration level at the leak orifice is given in Appendix A.

All detection, medium, and target parameters used in the analysis are given in Table 1.

TABLE 1. AEM SYSTEM MODEL PARAMETERS

PROCESSOR

Receiver Bandwidth (W)	3000 Hz (1 - 4 kHz)
False Alarm Rate (FAR)	1 per 24 Hrs; 1 per year
Probability of Detection (PD)	90%
Integration Time (T)	3 Secs; 30 Secs; 3 Min.

MEDIUM

Soil Type	Density (g/cm ³)	Long. Velocity (cm/sec)	Absorption (dB/kHz-Foot)
Moist Clay	1.75	14.94 x 10 ⁴	- 2.23
Dense Sand & Gravel	1.65	4.88 x 10 ⁴	- 2.05
Wet Saturated Sand	1.60	2.87 x 10 ⁴	- 10.15

TARGET

Depth (Top-of-Tank)	20 Feet (Maximum)
Leak Orifice	1/32 inch +
Tank Diameter (OD)	10 - 12 Feet
Tank Length	50 - 90 Feet

A two-octave receiver bandwidth of 1 to 4 kHz was assumed to represent the portion of the leak spectrum with the greatest amount of acoustic energy available for detection of deep depth leaks, and to be sufficiently above most of the masking background noises.

Although three types of soil are depicted for analysis, emphasis will be placed on a ground model comprised of dense sand and gravel (30 - 60 % gravel, plus sand and silt).

The leak orifice will be assumed to be circular in cross-section, and at the bottom of the tank. The leak geometry will simplify calculations, without too much loss in generality; it's location will maximize the attenuation and spreading losses for worst case analysis. The results can be easily modified to include the effect of a linear ("slit") orifice. Although a maximum depth of twenty feet was assumed from the ground surface to the top of the storage tank, most tanks are between four to eight feet.

2. Soil Attenuation

The attenuation of a compressional wave in soil depends upon the longitudinal velocity, soil density and moisture, and the frequency of the propagating wave. Assuming a geometric mean frequency of 2000 Hz (for a system frequency range of 1000 - 4000 Hz), the various attenuation loss mechanisms are estimated in Figure 9 for a concrete surface thickness and ground depth of 0 - 6 inches and 0 - 32 feet, respectively.

Analysis shows that a surface layer comprised of concrete

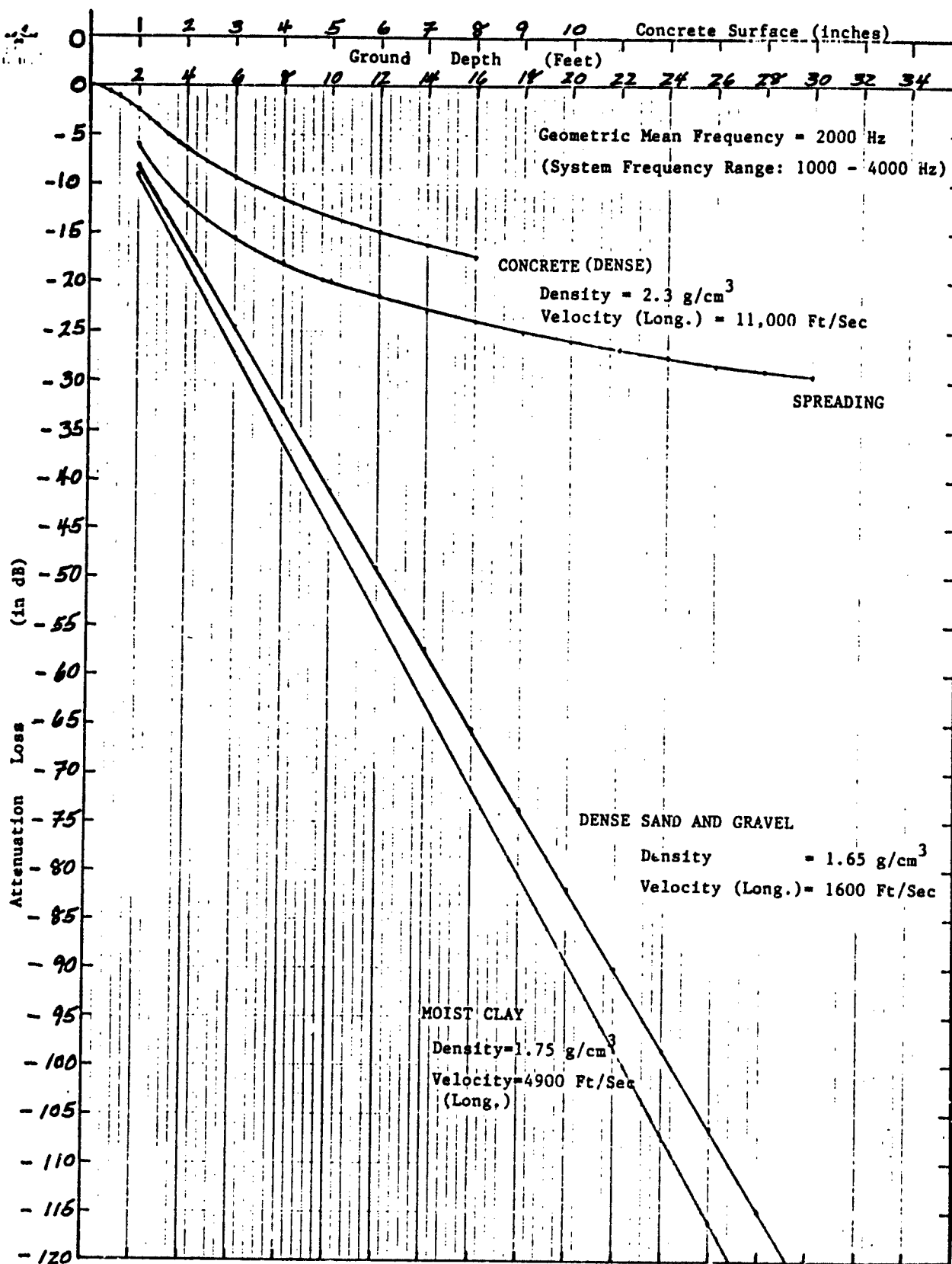


Figure 9. Attenuation Losses For Underground Acoustic Emission Signals

will greatly attenuate the acoustic leak signature; a layer thickness of only six inches will result in a loss of 15 dB. Thus, an AEM surface subsystem should be designed with an acoustic waveguide to penetrate the concrete, into the soil, to eliminate this loss. The soil losses are rather high for dense sand and gravel and moist clay, making reliable (low false alarm rate) deep depth leak detection difficult. Surface AEM system design must therefore (1) maximize sensor sensitivity and acoustical signal processing gain, (2) minimize soil attenuation by employing acoustic waveguides to within a few feet of the storage tank, and (3) minimize masking noise interference.

3. Minimum Detectable Leak Levels

The minimum detectable particle acceleration levels (MDSL) at the leak site are shown in Figure 10 for several processor integration times. B&K accelerometer Model 4381, having a voltage sensitivity of 80 mv/g over a frequency range of 0.1 to 4800 Hz, was used in the study. The soil was assumed to be comprised of dense sand and gravel, with and without a concrete surface layer. It is seen that the MDSL increases slowly with the integration time. For example, for a zero-inch concrete layer and an MDSL of 0 dB (re 1-g), the corresponding maximum leak depth increases by only two feet as the integration time increases by a factor of sixty (from 3 seconds to 3 minutes).

A continuous broadband acoustic emission is generated by the turbulence of the fluid escaping from the fuel tank. The greater the turbulence, the greater the pressure drop, and the greater the acoustic level created. The greatest pressure difference will occur from just inside the tank to just outside the tank.

Utilizing the model formulated by Morse and Ingard for the generation of acoustic power due to turbulent flow (described by Lighthill as quadrupole radiation), the following relationship was derived between the particle acceleration (\ddot{u}) and the volumetric discharge rate (Q) from a leak orifice of area (A) and diameter (D):

$$|\ddot{u}| = \left(\frac{K_p}{D} \right) \left(\frac{Q}{A} \right)^2 ; \quad K_p = \frac{2 \times 10^{-12}}{C^5}$$

where (C) is the velocity of sound in the escaping fluid. The derivation of this relationship is given in Appendix B.

In order to detect leak rates about 0.1 gallons per hour, the signal-to-"electronic" noise ratio (SNR) must be increased by at least 10 dB over that computed in the analysis (see Appendix A) to account for losses in the processor. The most direct way to increase the SNR by this amount is to employ an accelerometer having a voltage sensitivity at least three times greater than that considered. A candidate sensor for achieving this is B&K Model 4379, whose

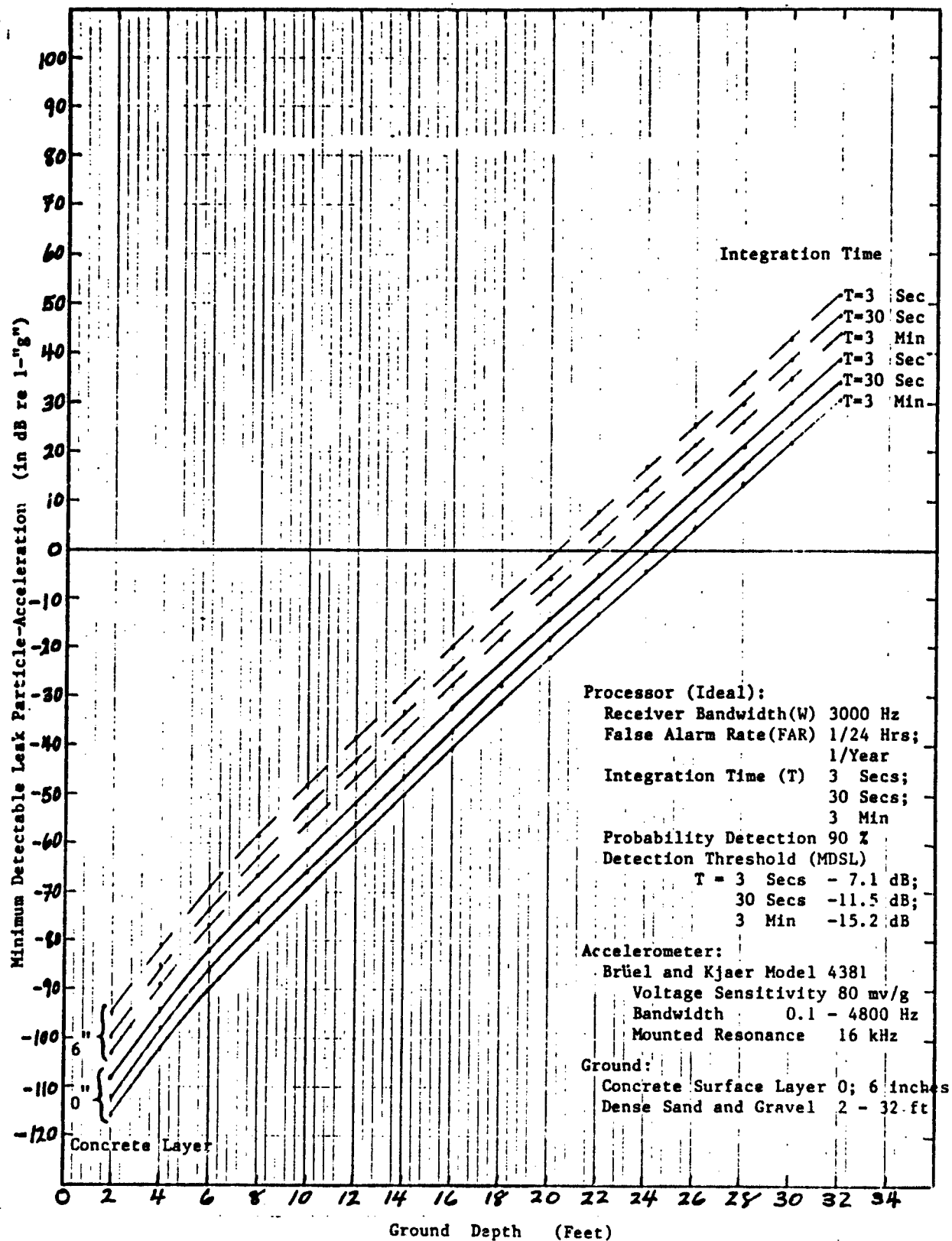


Figure 10. Minimum Detectable Leak Levels

sensitivity is given as 260 mv/g. The above equation indicates that by coupling such an accelerometer directly to the storage tank, a discharge rate of 0.3 - 0.4 gallons of JP-4 fuel per hour can be detected with 99% probability from a leak orifice of 1/32 inch. For smaller leak sizes, discharge rates less than 0.1 gallons per hour can be detected for a given detection threshold and accelerometer sensitivity.

C. Accelerometer Element Design And Coupling

The literature survey showed that acoustic emissions have a duration of approximately 0.25 to 10.0 milliseconds. This requires an accelerometer whose frequency response is from 100 to 4000 Hz. This band is compatible with the structural wavelengths of the steel storage tank and with the estimated processing band most effective for receiving acoustical signals propagating through the surrounding soil.

Discussions with B&K indicated that accelerometer Model 4379 is most appropriate for the proposed AEM application. Some of the characteristics for this sensor are given below:

<u>Sensor Characteristic</u>	<u>Model 4379</u>
Weight	175 grams
Voltage Sensitivity	260 mv/g
Frequency Range	0.1 - 3900 Hz
Mounted Resonance	13 kHz
Ambient Temperature	-50 to 250° C
Piezoelectric Material	PZ 23
Base Material	stainless steel (AISI 316)

After identifying the required AEM accelerometer, the question of coupling was addressed. The method of mounting the accelerometer to the measuring point is one of the most critical factors in obtaining accurate results from practical vibration measurements. A poor mounting results in a reduction in the mounted resonance frequency and thus limits the operating frequency range of the accelerometer. For the application studied here, the recommended mounting method is cementing the stud by using a hard glue. Consideration was also given to a hand-held acoustic waveguide with the accelerometer mounted on top and the bottom of the probe touching the tank. Based upon the attenuation of longitudinal waves in a steel tank and the required 99% detection threshold, it is estimated that the acoustic waveguides should be spaced about every twenty feet along the tank. Although this approach will be very convenient for quick survey work, it will tend to give gross measuring errors with minimal repeatability, and a very limited frequency response. For example, a mounted resonance of 16 kHz with a cement mount will probably be reduced to 1 kHz with a hand-held mount.

D. LEAK SIGNATURE PROCESSING

1. Product Array Processor

An investigation was made to determine whether product array (or correlation) processing can be used to detect and locate underground leaks. This requires that the AE propagated energy have some degree of spatial, temporal, and frequency coherence at the array sensors. Work performed by the Institute of Gas Technology (Reference 18) showed that high pressure gas leaks (greater than 15 psig), just three to four feet below the ground surface, were totally uncorrelated at distances five feet apart. In general, the correlation process is not efficient for signals propagating through soils because of the anisotropy of the various propagation paths and the rapid attenuation of the higher frequency components in the leak signal. This produces a correlogram which is unreliable and very difficult to interpret. If we extrapolate this information to a 90 foot storage tank, a Product Array Processor, such as a split-beam correlator (often employed in passive sonar for broadband acoustic detection), would require a very large number of sensors and processing channels, thus making it not very cost-effective for this application.

It became clear in the study that AE detection and monitoring should be accomplished by processing the Fourier spectra of the AE signatures from the outputs of a minimum number of strategically positioned sensors on the storage tank or pipeline. The Fourier processor architecture must also provide a capability to discern and minimize the various noise sources through selective frequency filtering, temporal gating, amplitude thresholding, and comparisons between long-time and short-time energy integration. These techniques have been successfully incorporated in current operational sonar systems.

2. Fourier Spectrum Processor

The Fourier Spectrum Processor (FSP), shown in Figure 11, has proven to be very effective for processing transient signals, such as AE signatures. It is a spectral peak detection type system which would be operated over the frequency band of 1 to 10 kHz. Based upon the attenuation of the high frequency spectral energy, the effective portion of the leak spectrum available for processing is expected to be well below 10 kHz. The FSP would be comprised of the following sub-systems: Input Signal Conditioning Unit (ISCU), Spectrum Analyzer Unit (SAU), and Post Processing Unit (PPU). The ISCU accepts acoustic data and performs receiver bandlimiting, automatic gain control, range gating and A/D conversion. These signals are sent to the SAU where all processing is performed digitally. It is estimated that a fast Fourier transform (FFT) algorithm with less than 512-points will be required to compute the magnitude of the DFT. The PPU accepts signals from the SAU and is capable of performing the following functions:

Short-Term Integration, Long-Term Integration, Automatic Threshold Detection and Noise Spectrum Rejection. Frequency line tracking (FLIT) and pattern recognition algorithms can be employed at this point to assist in mapping the leak migration and classifying the source leaks, respectively.

The Fourier Spectrum Processor was analyzed to determine the various losses associated with operational constraints and compromises in practical AEM system implementation. These losses are attributed to realizable bandpass filter responses, finite observation times, filter scalloping, finite averager sampling rates, detector characteristics, and the variation with detection probability:

Losses

Filter bin response (Hanning weighting)	0.17 dB
Finite observation time (3-minute time constant)	0.49
Averager sampling rate (2:1 redundancy)	0.25
Detector characteristic (linear)	0.20
Probability of detection (99%)	1.33
Scalloping (average)	0.50
	<hr/> - 2.94 dB

Thus, taking the above factors into account, the detection thresholds given in Figure 9 should be effectively reduced by 3.0 dB.

E. AEM SYSTEM SPECIFICATIONS

A realizable AEM system for the proposed application will be comprised of both a sub-surface and a surface FFT receiver, continuously monitored through an automatic threshold detection system. The first will require several accelerometers cemented to the storage tank, ideally located at the section welds. The second will employ acoustic waveguides, each containing an accelerometer, which can also be employed for portable operation. If the waveguides are in contact with the tank, they will pick up the induced vibrations when the tank is in a "plastic" state. If they are several feet away (but less than 5 feet) they will respond to the hydrodynamic noise produced by the escaping fluid.

The primary emphasis of an AEM system architecture for the proposed application is to efficiently process the AE signatures and discriminate against the various noise sources. Based upon AFESC requirements, the desired AEM system specifications are given in the following table.

TABLE 2. AEM SYSTEM SPECIFICATIONS

PERFORMANCE

Maximum Leak-Sensor Separation	5 feet
Minimum Leak Rate	0.1 gallon per hour
Pinpointing Accuracy	±2 feet
Resolution (Multi-Leaks)	4 feet apart
Accelerometer Sensitivity	250 mv/g (minimum)
Accelerometer Bandwidth	100 - 4000 Hz
Leak Detectability	99%
False Alarm Rate	
Portable (1 per day)	10^{-6} sec ⁻¹
Fixed (1 per year)	10^{-6} sec ⁻¹

OPERATIONAL (PORTABLE OR FIXED)

Temperature	- 40 to + 85° C
Relative Humidity	Must operate 0 to 100 %
Sensor Coupling	Cement to tank; Acoustic waveguide

PORTABLE OPERATION

Power Source	Rechargeable batteries
Power Consumption	Minimum of one day
Size	12" x 12" x 12"
Weight	30 pounds
Ruggedness	High-impact plastic case

The maximum leak-sensor separation implies the greatest distance the acoustic waveguides can have with respect to the leak site to detect the minimum leak rate given. This was determined by calculating the acoustic noise MDSL produced by turbulent fluid flow through the leak orifice (see Figure 10). It is anticipated that the minimum leak rate can be further reduced if the accelerometers are mounted directly on the storage tank. If a pipeline is buried within five feet of the surface, then the accelerometer(s) can conceivably be mounted at the ground surface level, which would permit portable operation. The resolution specified considers the multi-leak condition when there is a distributed system of storage tanks on the air force base, and there are simultaneous leaks from adjacent tanks. The sensitivity and bandwidth of the accelerometer should be sufficient to respond to the expected acoustic emissions from a storage tank (90 feet long with an outside diameter of 10 to 12 feet) due to tension, bending, compression, torsion, and rupture. The required receiver bandwidth will depend upon optimizing the signal-to-noise ratio at the Fourier processor input. The leak detectability specified is similar to that required by the AFESC, namely, 99%. However, the false alarm rates specified for portable and automatic

operation are significantly more stringent, and will result in greater reliability and minimum expenses incurred, in man-hours and mean-time-to-"repair", due to false positive readings.

The operational specifications insure robust AEM operation for a variety of weather conditions. Industrial-grade integrated circuits will be sufficient to achieve this reliability.

Portable operation requires that the field instrument be lightweight, water/dust resistant, and battery-powered. Energy consumption must be minimized, thus requiring CMOS integrated circuits. The device should be able to be continuously operated 8 hours per day, and permit overnight battery charging.

F. MASKING NOISE AND INDUCED STRESSES IN UNDERGROUND STORAGE TANKS

After a thorough review of the technical literature, it is quite clear that there are distinctive AE signatures that are induced in the tank due to internal and external stresses which can be sensed by properly designed accelerometers. The induced stresses in the tanks may be characterized as man-made and naturally-occurring disturbances, and also attributed to pipe corrosion and pipe wear. Measuring these signatures in a "noise free", laboratory controlled environment will not establish proof-of-concept. The real question is whether AE signatures can be discerned with high probability, and low false alarm rates, in an operational environment. For the application of detecting leaks in underground storage tanks on an Air Force base, the signatures will be masked and/or contaminated by a broad range of noise sources, namely:

MASKING NOISE (MAN-MADE AND NATURALLY-OCCURRING DISTURBANCES)

1. Air-borne
2. Transmitted vibrations from plant sources (e.g., pump station)
3. Wind conditions
4. Passing trains
5. Trucks, automobile
6. Earthquake
7. Nearby excavation
8. Nearby blasting
9. Direct impact - soil compaction

A preliminary investigation found that the highly fluctuating noise from aircraft flyovers (Reference 23), the relatively steady noise from a motorway with constant traffic density (Reference 24), the low frequency vibrations from a pump station (Reference 25), and the noise due to truck tire vibrations (Reference 26) will produce a broadband non-stationary interference level over the accelerometer frequency band specified (refer to Table 2). The portions of these

noises which are coupled to the ground will be strongly attenuated as they propagate through the soil, thereby enhancing the SNR at the sensors.

A realizable AEM system must be able to eliminate as much as possible all sources of man-made and naturally-occurring disturbances. This will require the use of techniques such as frequency filtering, time gating, multi-amplitude thresholding, frequency line tracking, and multi-sensor correlation (times-of-arrival). A successful Phase 2 program must emphasize the characterization and suppression of these environmental noise sources.

SECTION III

PHASE 2 AEM SYSTEM TEST PLAN

A. INTRODUCTION

The block diagram of the AEM system proposed for testing and evaluation in Phase 2 is shown in Figure 12. The system configuration will provide multi-sensor/channel data acquisition and Fourier processing to establish the presence of a fuel leak by the manned and unmanned detection of both high-level acoustic emission transients (bursts) and leak noise signatures. System design will automatically capture the leak signature, triggering a leak alarm. Measurements will determine the MDSL's and corresponding leak rates for the various noise sources identified in Section II.F.

Laboratory testing and calibration will require the construction of a ground model to make critical measurements while simulating leak and environmental noise conditions. Another part of the test and measurements phase will be the acquisition (and possibly field recording) of environmental noise to be used for both ground model and field measurement of MDSL's. Data gained in ground model measurements will enable confirmation of the functional characteristics of the acoustic sensors (accelerometers, piezoelectric transducers, strain gauges) with interfacing circuitry. Preliminary system measurements will also provide an early measure of subsystem design rationale and enable circuit optimization.

Field testing will be carried out at an appropriate site (preferably at an airport) to verify the utility of the leak detection system under normal environmental conditions. The field test program will be designed to obtain quantitative measurements of the limits of leak detectability for two system modalities, ie., manned and unmanned operation.

B. TEST OBJECTIVES

Tests will be conducted at MSB's facility and at a field site approved by cognizant personnel at Tyndall AFB. The objective of these tests will be to:

1. Quantify minimum detectable leak rates for various noise sources, sensor characteristics and sensor locations, with the internal pressure and leak size as parameters.
2. Measure false alarm rates, with receiver bandwidth and integration time as parameters.
3. Quantify performance of manned and unmanned operation in terms of dynamic range, MDSL, and FAR for a given leak rate.

The storage tank will be standard in size (90 feet long with 10 to

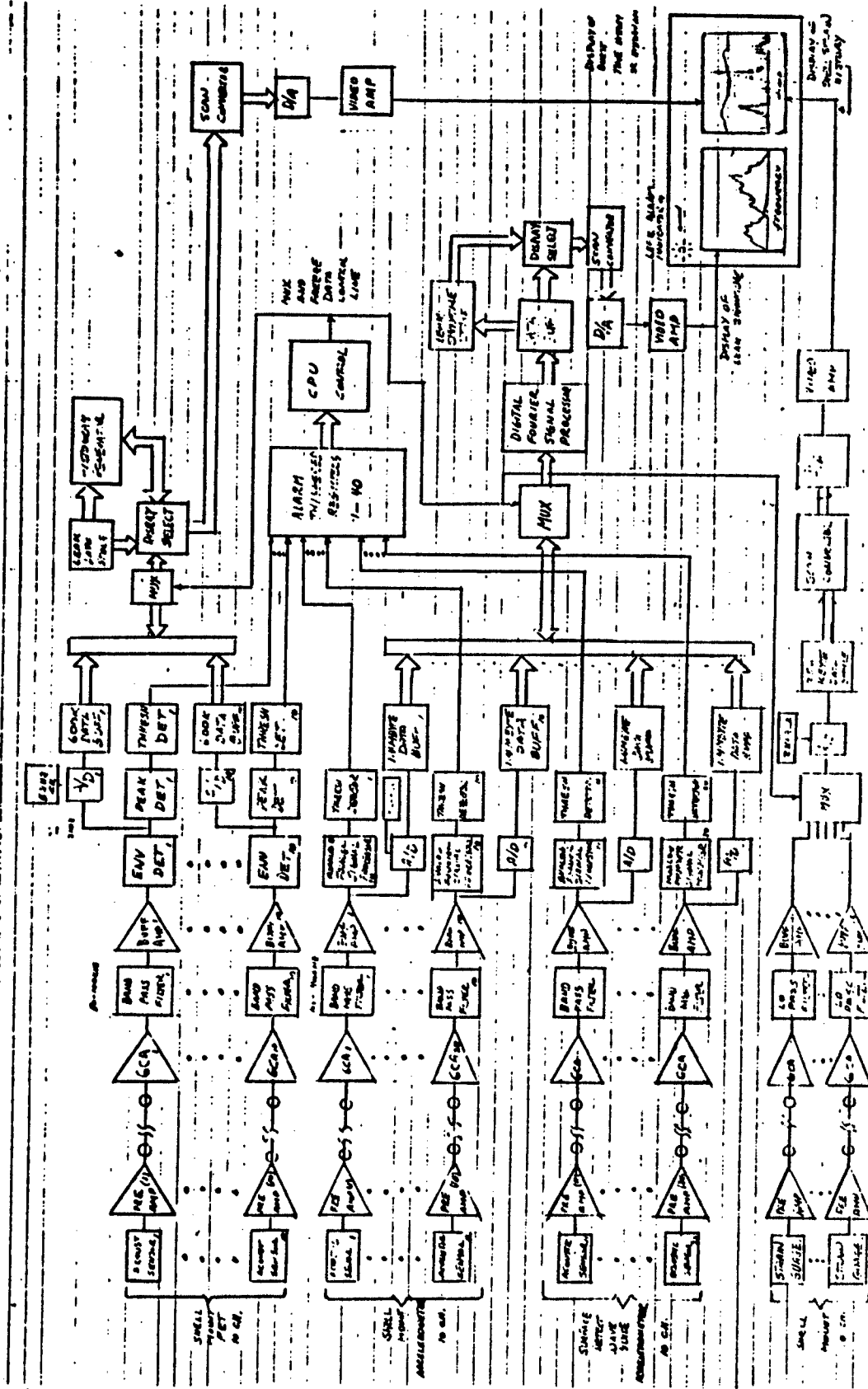


Figure 12. AEM System Configuration for Testing and Evaluation in Phase 2

12 feet OD) and liquid fill level. The test tank will have a remotely operated leak turn-on/off capability and will facilitate the installation of 40 sensors both on its hull and in the nearby soil.

A comprehensive set of recordings will be made of leak signatures and noise sources, including air-borne, ground motor traffic and plant station, at the field test site(s). This will facilitate the assessment of various signal processing and noise discrimination techniques during the Data Processing task.

C. TEST DESCRIPTION

1. Laboratory Tests

Following normal electrical testing at the circuit card and subsystem function level, system performance will be evaluated at NSB with the aid of a ground model.

The ground model is shown in Figure 13. The model consists of a one foot by two foot by three foot wooden earth container with a steel or fiberglass cover made of tank hull material. The wooden container is fitted with aluminum end plates to facilitate the installation of waveguide sensors. The tank hull material will be fitted with a machined plug, including an orifice dimensioned and cut to generate turbulent flow. The plug is enclosed in a cylinder containing jet fuel (JP-4). Various tank pressure heads will be simulated by controlling the air pressure and piston combination.

The tank hull will be fitted with accelerometer and piezoelectric sensor mounts at various distances from the leak plug. Each preamplifier will be located next to its sensor and will include a low impedance noise injection port and noise monitor test point. The AEM system will include 20 low frequency (accelerometer) channels for leak signature detection (10 accelerometers cemented to the storage tank and 10 incorporated in acoustic waveguides), and 10 mid-frequency (piezoelectric transducer) channels for acoustic emission detection. An additional 10 channels will be included for strain gauges to pair with the acoustic emission sensors. The 30 low and mid-frequency sensors will operate with multi-threshold monitoring circuits that will generate an alarm pulse when preset thresholds are exceeded.

Initial tests will measure MDSL's, as shown in Figure 14. A test noise generator will be connected to the preamplifier input noise port and set to a predetermined power level equivalent to the anticipated environmental noise power level. A test signal generator will substitute for the acoustic sensor and be adjusted to generate a threshold alarm signal as seen at the output of the Fourier Spectrum Processor or burst detector. Detected alarm counts are stored in the alarm registers and read out via an IEEE 488 interface to a peripheral computer. These measurements will be made using white noise

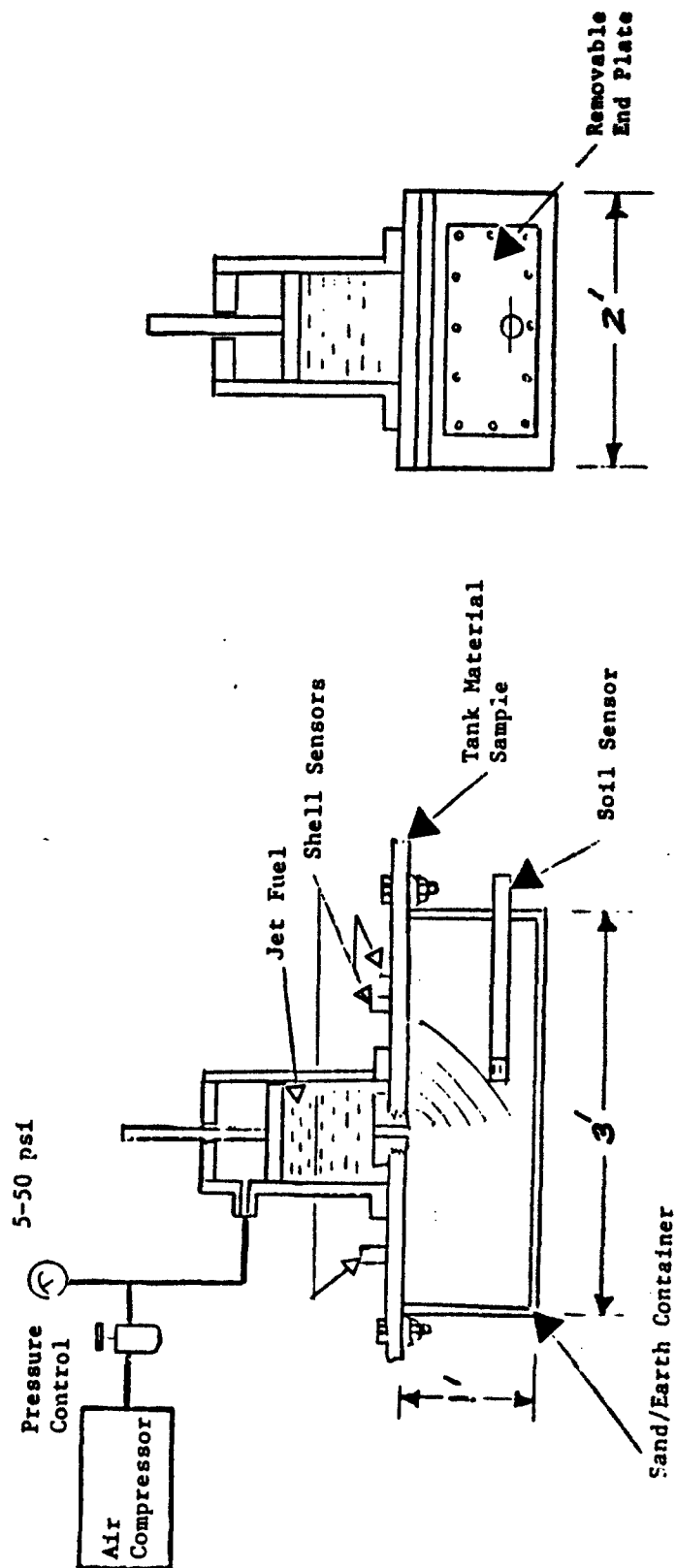


Figure 13. AEM Ground Model

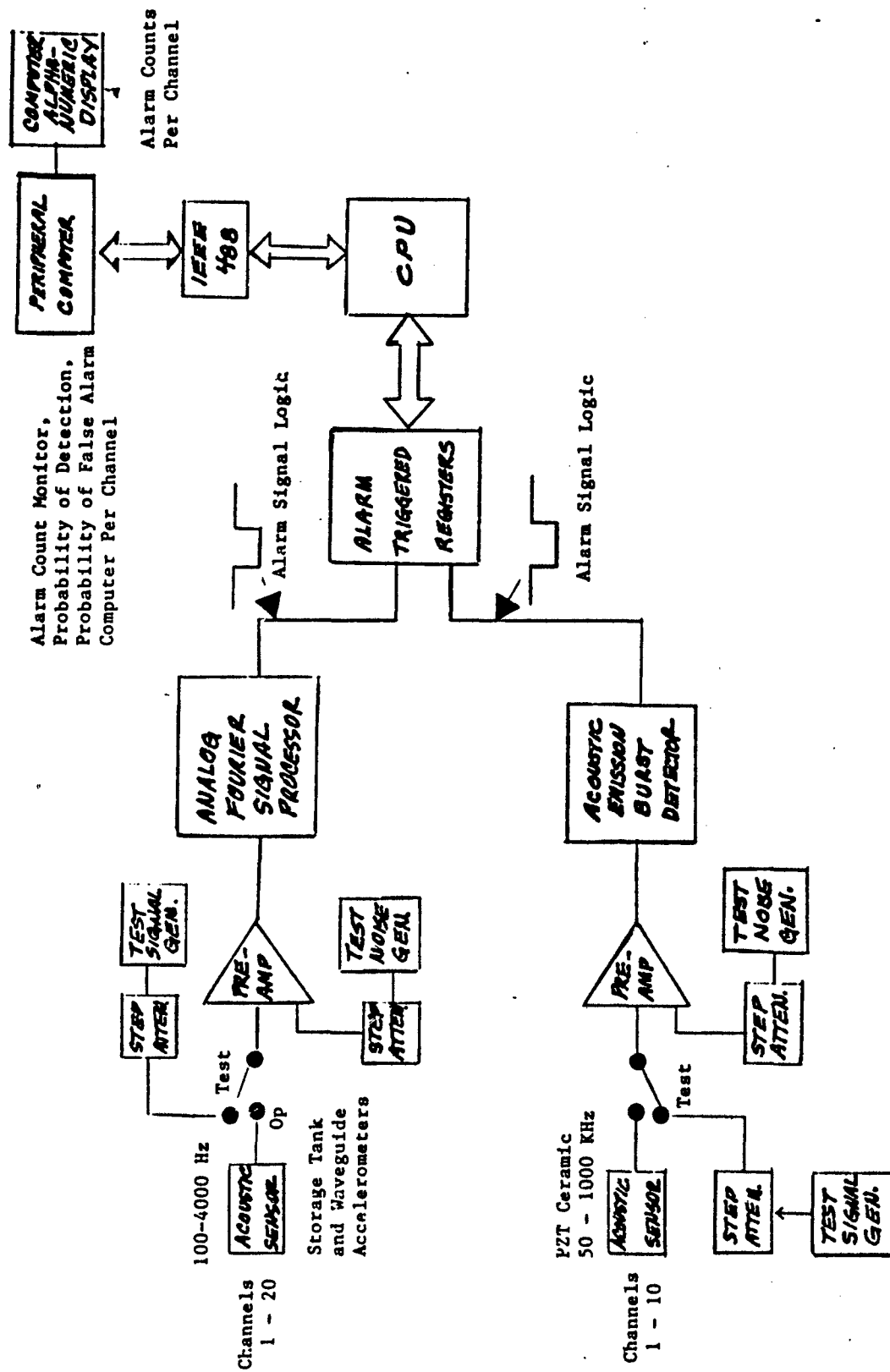


Figure 14. Minimum Detectable Signal Level and False Alarm Measurement

generators and repeated with recordings of true ambient noise where possible. Similar testing will be done of the manned portion of the system which includes continuous sampled data storage of the most recent 3 minutes of signal information on each channel. The stored data of each channel will be displayed for approximately 3 minutes, producing a running time history of all signals in the system (see Figure 12). In the event of an alarm, data acquisition is stopped within 10 seconds following the alarm event in order to record a sample of subsequent events for comparison with the alarm event. Long term false alarm measurements will also be made with the measurement system in Figure 14. This will be accomplished by turning the signal off and measuring the False Alarm Rate as a function of noise power, threshold level, and receiver bandwidth.

Detectable leak rates predicted from the model derived in Phase 1 will be extrapolated from measured MDSL'S for various masking noise sources and confirmed by measurements with the ground model. A summary of test results will be submitted to define a Field Test Program.

2. Field Tests

Field tests will require the cooperation of cognizant personnel at Tyndall Air Force Base (TAFB) and will follow a carefully outlined test protocol prepared by MSB Systems, reviewed and approved by TAFB. The emphasis in this task will be to verify reliable (repeatable) detection of low leak rates (less than 0.1 gallons per hour) under actual environmental conditions.

AEM system operation at the field site will require the installation and monitoring of 20 acoustic sensors and 10 strain gauges at preselected locations on the test tank. The designated test site will provide known and controllable leak situations and a broad spectrum of environmental noise sources. Signal and noise levels will be continuously recorded during testing to verify the levels which generate automatic alarm situations. For example, the pump noise generated by a known installation, operating at pre-determined pump rates, will be completely characterized. Testing will include an evaluation of manned and unmanned operation, and of the automatic alarm function (multi-threshold detection), with observation of the spectral and time representations and histographic displays. Measurement of minimum detectable leak rates versus noise power will be made for both modalities.

Data will be collected at both the field and ground model test sites to permit calculation of the Minimum Detectable Signal Level (MDSL), the Probability of Detection (PD) and the Probability of False Alarm (PFA) as a function of Noise Power. A typical data collection/summary format for each primary noise source is given in Table 3.

TABLE 3. TYPICAL DATA COLLECTION/SUMMARY FORMAT FOR EACH AMBIENT NOISE SOURCE

Leak Rate (GPH)	CH# _____ NOISE SOURCE # _____ TYPE _____ PSI _____ MEAS BAND LEVEL _____ dBm 3 dB BANDWIDTH _____ KHZ															
	PRESSURE HEAD															
	MINIMUM DETECTION LEVELS (MDSL)								ALARM COUNT RATE (C/M)							
	Acoustic Emission Level		Fourier Spectral Level			Acoustic Emission Level			Fourier Spectral Level			Acoustic Emission Level		Fourier Spectral Level		
	Calcul Level dBm	Meas Level dBm	Lo Band dBm	Mid Band dBm	Hi Band dBm	Cal dBm	Meas dBm	Lo Band dBm	Mid Band dBm	Hi Band dBm	Cal dBm	Meas dBm	Lo Band dBm	Mid Band dBm	Hi Band dBm	
	X ₀	X ₁	X ₂	Z ₀	Z ₁	Z ₂	Q ₀	Q ₁	Q ₂	Q ₃	Q ₄	Q ₅	R ₀	R ₁	R ₂	
0.01																
0.02																
0.03																
0.04																
0.05																
;																
0.50																

Data based on zero leak flow (no rupture) will be collected at the ground model site for various simulated pressure heads, and repeated at the field site for actual limited-pressure heads. A typical data collection format of leak precursor AE bursts is given in Table 4.

TABLE 4. MEASUREMENT OF LEAK PRECURSOR ACOUSTIC EMISSION SIGNALS WITH GROUND MODEL

<u>PRESSURE HEAD</u> (PSI)	<u>LEAK FLOW RATE</u> (GAL/HR)	<u>AE ENERGY</u> (WATT-SEC)	<u>AEM ALARM RATE</u> (COUNTS/MIN)
P_{min}	0	W_{min}	R_0
.	.	.	.
.	.	.	.
P_{max}	0	W_{max}	R_N

NOTE: Noise level ____ dBm; 3dB Bandwidth ____ kHz

The PFA in Table 3 will also be measured as a function of noise frequency and spectral power level at zero leak flow. A variable pressure head is used to measure the effect of low frequency acoustic emission on the PFA. Final data assessment will provide a clear estimate of minimum detectable leak rate as a function of background noise.

3. Data Processing

The collected data base will be further analyzed at MSB to derive the information-bearing attributes contained in the AE signatures. The various significant parameters and the type of information they reveal have been discussed by Stephens and Pollack (Reference 27) and are given in Table 5 below.

TABLE 5. PARAMETERS RELATING TO AE SIGNALS

<u>EMISSION PARAMETER</u>	<u>TYPE OF INFORMATION</u>
Waveform	Fine structure of source event
Spectrum	Nature of source event
Amplitude	Energy of source event
Amplitude distribution	Type of damage occurring
AE burst rate	Rate of damage occurring
Pulse distribution in time	Type of damage occurring
Multisensor arrival times	Source location

Additional features will be obtained by examining the ratio of

peak amplitude and energy from pairs of sensors in various time intervals and frequency bands.

The time and frequency domain features discussed may also be used with standard pattern recognition algorithms to classify AE signatures according to their source types. Elsley and Graham (Reference 28) had considerable success in applying these methods to discriminating between the AE bursts generated by two close AE sources in a section of an aircraft structure, namely, between the AE due to a fatigue crack growing from the edge of a fastener hole and the AE due to fastener fretting in the hole. Classification of labeled data produced a 96 - 100% accuracy, and clustering of unlabeled data produced an 82 - 94% accuracy. MSB intends to utilize its Pattern Recognition Software developed in its medical imaging and undersea target classification programs to develop and test classification algorithms for the AEM problem studied here.

D. ENVIRONMENTAL IMPACT/SAFETY

Field testing will have a minimal impact on the test site environment. There will be forced jet fuel leakage into a controlled small space which is estimated to be less than 100 square feet. It is planned that this leaked jet fuel will be routed to a collection sump and not be allowed to percolate to deep streams. Noise will be generated for test purposes but it will be no worse than present normal levels for the designated test site. Jet fuel will be used during ground model testing at MSB and all necessary requirements for safe storage and handling required by the State of Connecticut will be adhered to.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based upon the results of the study, it has been well established that distinguishable AE signals will be generated when the storage tank is subjected to stresses, such that it undergoes deformation. These transient signals should be sensed with an array of accelerometers (cemented to the tank or via acoustic waveguides), each having a sensitivity greater than 250 mv/g over a frequency range from 0.1 to 4000 Hz, and processed in a multi-channel Fourier spectrum analyzer with automatic threshold detection. The proposed AEM system will permit a probability of leak detection of 99% and a false alarm rate less than 10^{-5} (1 per day) for leak discharge rates less than 0.1 gallons per hour (leak sizes less than 1/32 inch). An acoustic transient or energy release processor could conceivably detect the onset of the leak at the moment of the fracture of the tank wall.

The primary limitations to realizing reliable and robust AE monitoring of underground fluid leaks are the various masking noise sources prevalent at field sites. These noises are attributed to aircraft, motor traffic, pump station operation, and ground tremors.

A realizable AEM system must be able to eliminate, as much as possible, all sources of man-made and naturally-occurring disturbances. This will require the use of signal processing techniques such as frequency filtering, time-gating, multi-amplitude thresholding, frequency line tracking, multi-sensor correlation (times-of-arrival) and pattern recognition algorithms for noise source classification. The operational effectiveness of these techniques has been proven in the fields of sonar and radar.

B. RECOMMENDATIONS

It is recommended that the Phase 2 effort primarily address the measurement, characterization and suppression of the identified masking noise sources. A noise signal library should be compiled from measurements taken at actual field sites and provide input for post-detection algorithmic processing.

A rugged, high sensitivity fiber-optic hydrophone has been successfully developed by the U.S. Navy (Naval Research Laboratory) to detect low frequency radiated underwater acoustic signals. This suggests that a special fiber-optic sensor can be developed to provide ultra-high sensitivity to acoustic vibrations in order to overcome the low signal-to-noise problems associated with small fluid leaks. A single mode interferometric configuration appears to be the most promising design approach for this application. If successfully

developed, it will permit the reliable detection of leak discharge rates approaching 0.01 gallons per hour over a broad range of operational and environmental noise conditions.

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APPENDIX A

DERIVATION OF MINIMUM DETECTABLE LEAK PARTICLE ACCELERATION LEVEL

A. INTRODUCTION

The parametric analysis performed in the study is based upon the AEM model shown in Figure 8. The objective is to detect a radiating acoustic leak signature with high probability (PD) and low false alarm rate (FAR).

B. PROCESSOR

Based upon the results of the Technical Literature Review, the effective operating frequency range is assumed to be from 1000 to 4000 Hz. This results in a receiver bandwidth (W) of 3000 Hz.

The FAR is assumed to be less than once per 24 hours for a portable system, and once per year for an automatic detection system:

$$\text{FAR (portable)} = \frac{1}{24 \text{ hrs} \times 3600 \text{ secs/hr}} = 1.16 \times 10^{-5} \text{sec}^{-1}$$

$$\begin{aligned} \text{FAR (automatic)} &= \frac{1}{1 \text{ yr} \times 365 \text{ days/yr} \times 24 \text{ hrs/day} \times 3600 \text{ secs/hr}} \\ &= 3.17 \times 10^{-8} \text{sec}^{-1} \end{aligned}$$

The probability of false alarm (PFA) is computed as the product of the processor integration time (T) and the FAR. The PFA's are given below for practical integration times of three seconds, thirty seconds and three minutes. The smallest processor time is approximated for portable operation, while the other times are suitable for an automatic mode.

$$\begin{aligned} \text{PFA (portable)} &= \text{PFA}_3 = 3 \text{ secs} \times 1.16 \times 10^{-5} \text{sec}^{-1} \\ &= 3.5 \times 10^{-5} \end{aligned}$$

$$\begin{aligned} \text{PFA (automatic)} &= \text{PFA}_{30} = 30 \text{ secs} \times 3.17 \times 10^{-8} \text{sec}^{-1} \\ &= 10^{-6} \end{aligned}$$

$$\begin{aligned} \text{PFA (automatic)} &= \text{PFA}_{180} = 180 \text{ secs} \times 3.17 \times 10^{-8} \text{sec}^{-1} \\ &= 6 \times 10^{-6} \end{aligned}$$

For purposes of establishing the significance of the various AEM system parameters, the probability of detection (PD) is initially required to be 90%. Tradeoffs can later be made between PD and PFA, for a given detection threshold.

To detect the amplitude modulation of the acoustic emissions, an ideal incoherent processor is assumed. The required post processor

thresholds (PT) are obtained from the classical standard receiver operator characteristic, assuming Gaussian statistics:

$$\begin{aligned}PT_0 &= 12.7 \text{ dB} \\PT_{00} &= 13.3 \text{ dB} \\PT_{100} &= 13.5 \text{ dB}\end{aligned}$$

The processing gain (G) depends on the bandwidth - integration time product, which can be estimated as:

$$G = 5 \log WT$$

For the parameters chosen,

$$\begin{aligned}G_0 &= 5 \log (3000 \times 3) = +19.77 \text{ dB} \\G_{00} &= 5 \log (3000 \times 30) = +24.77 \text{ dB} \\G_{100} &= 5 \log (3000 \times 180) = +28.86 \text{ dB}\end{aligned}$$

The detection threshold (DT) is the minimum detectable signal-to-noise power ratio at the output of the sensor for a given PD and PFA, and is computed as:

$$DT = (\text{Post-Threshold}) - (\text{Processing Gain})$$

For the specified AEM operation,

$$\begin{aligned}DT_0 &= -7.1 \text{ dB (0.195)} \\DT_{00} &= -11.5 \text{ dB (0.0708)} \\DT_{100} &= -15.2 \text{ dB (0.0302)}\end{aligned}$$

The power ratios are given in parentheses.

C. THERMAL NOISE ESTIMATION

The rms thermal noise (N_{th}) is expressed as:

$$N_{th} = \sqrt{4RKTW}$$

where K = Boltzmann's constant = 1.37×10^{-23} watt-seconds/degree
 T = absolute temperature = $(C^\circ + 273.1^\circ)$ Kelvin
 W = receiver bandwidth = 3000 Hz
 R = sensor resistive impedance = 400 ohms

For an ambient temperature of 30°C ,

$$N_{th} = 0.1414 \text{ microvolts (rms)}$$

D. MINIMUM DETECTABLE LEAK PARTICLE ACCELERATION LEVEL

If S is the signal power at the output of the sensor, then

$$\frac{S}{N_{th}^2} = DT \text{ (power ratio),}$$

and the rms signal level \sqrt{S} , for the various processor integration times, is computed to be:

$$\sqrt{S_s} = 0.0624 \text{ uv}$$

$$\sqrt{S_{so}} = 0.0376 \text{ uv}$$

$$\sqrt{S_{sso}} = 0.0246 \text{ uv.}$$

If we assume an accelerometer with the characteristics of B&K Model 4381, which has a voltage sensitivity of 80 mv/g over a frequency range of 0.1 to 4800 Hz, the minimum detectable acceleration levels (\ddot{u}_0) at the accelerometer/soil interface are:

$$|\ddot{u}(0)|_s = \frac{0.0624 \text{ uv}}{8 \times 10^{-3} \text{ /g}} = 0.78 \times 10^{-3} \text{ "g"} \text{ (-122.2 dB/1-"g")}$$

$$|\ddot{u}(0)|_{so} = \frac{0.0376 \text{ uv}}{8 \times 10^{-3} \text{ /g}} = 0.47 \times 10^{-3} \text{ "g"} \text{ (-126.6 dB/1-"g")}$$

$$|\ddot{u}(0)|_{sso} = \frac{0.0246 \text{ uv}}{8 \times 10^{-3} \text{ /g}} = 0.31 \times 10^{-3} \text{ "g"} \text{ (-130.2 dB/1-"g")}$$

where "g" = 980 cm/sec². These are also the same acceleration levels which will be present if the accelerometer is placed directly on the storage tank.

Due to propagation losses in the soil, the detection sensitivity will decrease as the storage tank depth increases. The resulting minimum detectable leak levels as a function of ground depth are shown in Figure 10. The propagation losses were computed using the models given below in (E).

E. PROPAGATION LOSSES

1. Concrete Surface Layer

Consider the soil to be paved with a layer of concrete and that the acoustic emission wave is normal to the accelerometer/layer surface. Then the loss in the on-axis acceleration level (α_s) propagating through the concrete layer can be computed as (Reference 30):

$$\alpha_s = \frac{|\ddot{u}(Z_s)|}{|\ddot{u}(0)|} = [1 + (KZ_s \rho_s / \rho)^2]^{-1/2}$$

where for soil comprised of dense sand and gravel:

ρ	= density in soil	= 1.65 g/cm ³
ρ_s	= layer density	= 2.30 g/cm ³
C_L	= longitudinal sound velocity in soil	= 4.88 x 10 ⁴ cm/sec
f	= geometric mean frequency	= 2000 Hz

K = wavenumber in soil = $2\pi f/C_L$ = 0.258 cm^{-1}
 Z_c = concrete layer thickness

For the parameters chosen, the loss in concrete is given by:

$$\alpha_c = [1 + 0.839 Z_c^2]^{-1/2} \quad (Z_c \text{ in inches}).$$

The attenuation of the AE signal through a surface layer of concrete as a function of layer thickness is shown in Figure 9.

2. Soil

Assuming spherical propagation waves, the AE pressure (p) at an arbitrary distance (z) from the leak may be expressed as:

$$p = p_0 \frac{e^{-\alpha f z}}{z}$$

where p_0 = pressure at leak orifice
 f = geometric mean frequency
 α = attenuation coefficient in soil = $\pi n/C_L$
 n = soil dependent loss factor
 C_L = longitudinal sound velocity in soil.

For soils comprised of moist clay and dense sand plus gravel (Reference 31):

$$\alpha(\text{moist clay}) = \frac{\pi \times 0.4}{14.94 \times 10^4} = 8.41 \times 10^{-6} \text{ neper-sec/cm}$$

$$\alpha(\text{dense sand and gravel}) = \frac{\pi \times 0.12}{4.88 \times 10^4} = 7.73 \times 10^{-6} \text{ neper-sec/cm}$$

The attenuation losses for underground AE signals, namely, those due to spreading and absorption are computed as:

$$\text{Spreading Loss} = -20 \log z \quad (\text{in dB}),$$

$$\begin{aligned} \text{Absorption Loss} &= 20 \log e^{-\alpha f z} \\ &= -8.686 \alpha f z \quad (\text{in dB}), \end{aligned}$$

and are shown in Figure 9 as a function of ground depth.

APPENDIX B

DERIVATION OF PARTICLE-ACCELERATION (\ddot{u}) FOR A VOLUMETRIC DISCHARGE RATE (Q) FROM A LEAK ORIFICE OF AREA (A)

A. PRESSURE FIELD AND ACOUSTIC POWER OF THE CIRCULAR PISTON

Consider the fluid flow from the leak orifice, and the associated radiated sound field, as sound radiation from a circular piston. The far-field pressure $p(R, \theta)$ is then given as (Reference 29):

$$p(R, \theta) = \frac{\rho \ddot{u} D}{2R} e^{jK R} \frac{J_1(KD \sin \theta / 2)}{K \sin \theta}, \quad KD \sin \theta \ll R$$

where

- ρ = fluid density
- \ddot{u} = fluid particle - acceleration
- D = circular piston diameter = $2a$
- K = wavenumber = $2\pi/\lambda$
- λ = wavelength = V/f
- V = fluid velocity
- f = frequency of propagating pressure wave
- J_1 = Bessel function of first kind, first order
- θ = polar angle with respect to the acoustic axis of circular piston
- R = radial distance from acoustic center of piston to field point

The above equation is derived from Rayleigh's formula (based on the Helmholtz integral equation):

$$p(\underline{R}) = \frac{\rho}{2\pi R} \int_{S_0} \exp(jK|\underline{R} - \underline{R}_0|) \ddot{u}(\underline{R}_0) dS(\underline{R}_0)$$

where $\ddot{u}(\underline{R}_0) dS(\underline{R}_0)$ is the volume acceleration of an area element of the source (S) and $\underline{R}_0 \ll \underline{R}$. This result implies that two-dimensional information can be used to construct an acoustic field that depends on these spatial variables.

The axial pressure $p(R, 0)$, where $R=Z$, becomes:

$$p(Z, 0) = \frac{\rho \ddot{u} D^2}{8Z} e^{jK Z}$$

The acoustic intensity $I(R)$ is defined as the power flow per unit area and is used as a measure of the properties of a directional source. The total emitted acoustic power on axis ($\Delta \pi_{00}$) for a circular piston is:

$$\Delta \pi_{00} = 4\pi R^2 I(R)$$

$$= 4\pi Z^2 |p(Z,0)|^2 / 2\rho c, \quad KZ \gg 1$$

$$= (\pi/32)(\rho/c)D^4 |\ddot{u}(Z)|^2$$

$$= (1/2\pi)(\rho/c)A^2 |\ddot{u}|^2$$

where (A) is the area of the leak orifice.

B. TURBULENT ACOUSTIC POWER

In a turbulent fluid, sound emissions and flow fluctuations are due to the instability of fluid flow. From Bernoulli's equation, a turbulent fluid with velocity (V) will produce a local acoustic pressure fluctuation of the order of:

$$p \approx (d/R)\rho V^2$$

where d = size of region over which pressure fluctuations occur
R = distance from the monopole source.

The corresponding radiated power (π_o) for a monopole source is:

$$\pi_o = 4\pi R^2 \frac{p^2}{2c\rho} = 2\pi d^2 \frac{\rho V^4}{c} = 2\pi \rho V^2 d^2 \left(\frac{V}{c}\right) \left(\frac{V}{d}\right)$$

Considering monopole, dipole, and quadrupole sound sources, the acoustic power is approximately:

$$\text{Monopole: } \pi_o \approx \rho V^2 d^2 (V/c)(V/d)$$

$$\text{Dipole: } \pi_d \approx \rho V^2 d^2 (V/c)^2 (V/d)$$

$$\text{Quadrupole: } \pi_q \approx \rho V^2 d^2 (V/c)^3 (V/d)$$

In each of these equations, the $\rho V^2 d^2$ term represents the fluid kinetic energy, the (V/c) term is the fraction of kinetic energy transformed into sound per unit time and the (V/d) term is the inverse characteristic time of the fluctuation.

A turbulent flow in a fluid generates the same sound field as a certain distribution of quadrupoles. The eighth power dependence for a quadrupole source was first proposed and formulated by Lighthill. The acoustic power is the sum of all of the power contributions of the uncorrelated eddies in the fluid.

The leak from an underground storage tank can now be considered as a problem in determining the level of sound emission from a turbulent jet with diameter (D) and average flow velocity (V). The acoustic kinetic energy discharged per second can be expressed as:

$$\pi_q = (\rho V^2 / 2)(\pi D^2 / 4)V \approx \rho V^2 D^2 (V/D)$$

The above analysis indicates that the fraction of this power (π_{AE}) radiated into sound is:

$$\pi_{AE} = KM^2(\rho V^2/2)A$$

where $M = V/c$ (local Mach number)

$K = \text{constant} \approx 10^{-4}$ for subsonic circular jets.

The efficiency of power conversion is about $10^{-4}M^2$, and π_{AE} becomes:

$$\begin{aligned}\pi_{AE} &= 10^{-4} \left(\frac{V}{c} \right)^2 \frac{\rho V^2}{2} A \\ &= \frac{10^{-4}}{c^2} \frac{\rho}{2} \frac{Q^2}{A^3}\end{aligned}$$

where $Q = AV = \text{rate of discharge}$.

C. VOLUMETRIC DISCHARGE RATE

A measure of the discharge rate can be obtained by equating the acoustic power of a circular piston and the turbulent acoustic power generated by the fluid flow. A field point near the leak orifice is chosen such that $D \ll R$. Equating the derived expressions for $\Delta\pi_{CP}$ and π_{AE} ,

$$(1/2\pi) (\rho/c) A^2 |\ddot{u}|^2 = \frac{10^{-4}}{c^2} \frac{\rho}{2} \frac{Q^2}{A^3}$$

which reduces to:

$$|\ddot{u}| = (K_p/D)(Q/A)^{1/2}$$

where $K_p = 2 \times 10^{-2}/c^2$.

$|\ddot{u}|$ is the magnitude of the leak particle acceleration level produced by turbulence through an orifice having a discharge rate Q . For a given fluid, ρ and c are defined, and K_p is a constant. This relationship, and the communication model developed for computing the minimal detectable acceleration level, are the primary results of the Phase I study. They can be used to assess the feasibility of employing AEM technology for detecting underground storage leaks and to design the Phase II experimental program (Section III).

Consider JP-4 jet fuel, which has the properties:

Kinematic viscosity (ν) = $9 \times 10^{-3} \text{ cm}^2/\text{sec}$
 Density (ρ) = 0.75 g/cm^3
 Velocity of sound (c) = $[1.1 - 1.4 \times 10^3 \text{ cm/sec}]$

flowing through a leak orifice of diameter $1/32$ inch. Utilizing the minimum detectable acceleration levels achievable with a Fourier processor that were computed in Appendix A, the above equation was used to estimate the following minimum detectable discharge rates for portable and automatic operation:

Q(3) - 0.40 gallons/hour
Q(30) - 0.35 gallons/hour
Q(180) - 0.32 gallons/hour

where the designation in parenthesis refers to the processor integration time. The analysis is based on the accelerometer having a voltage sensitivity of 80 mv/g, and ideal processing giving a 90% probability of detection. To account for processor losses and to obtain a probability of detection of 99%, the accelerometer sensitivity should be increased by a factor of three. Detectable discharge rates less than 0.1 gallons per hour can be achieved for leak sizes less than $1/32$ inch.